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(54) **SUBTERRANEAN MAPPING SYSTEM  
INCLUDING ELECTRICALLY CONDUCTIVE  
ELEMENT AND RELATED METHODS**

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**G01V 3/10** (2006.01)

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CPC ... **G01V 3/12** (2013.01); **G01V 3/10** (2013.01)

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USPC ..... 342/22, 27, 179–180, 191  
See application file for complete search history.

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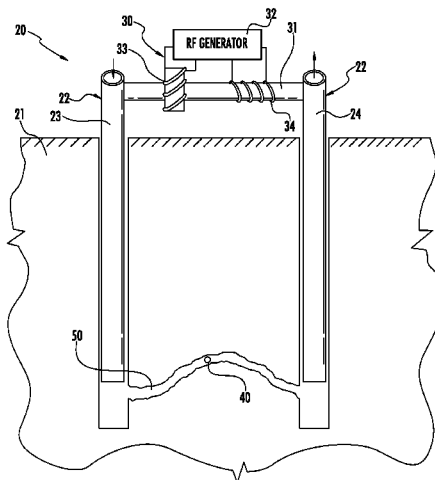
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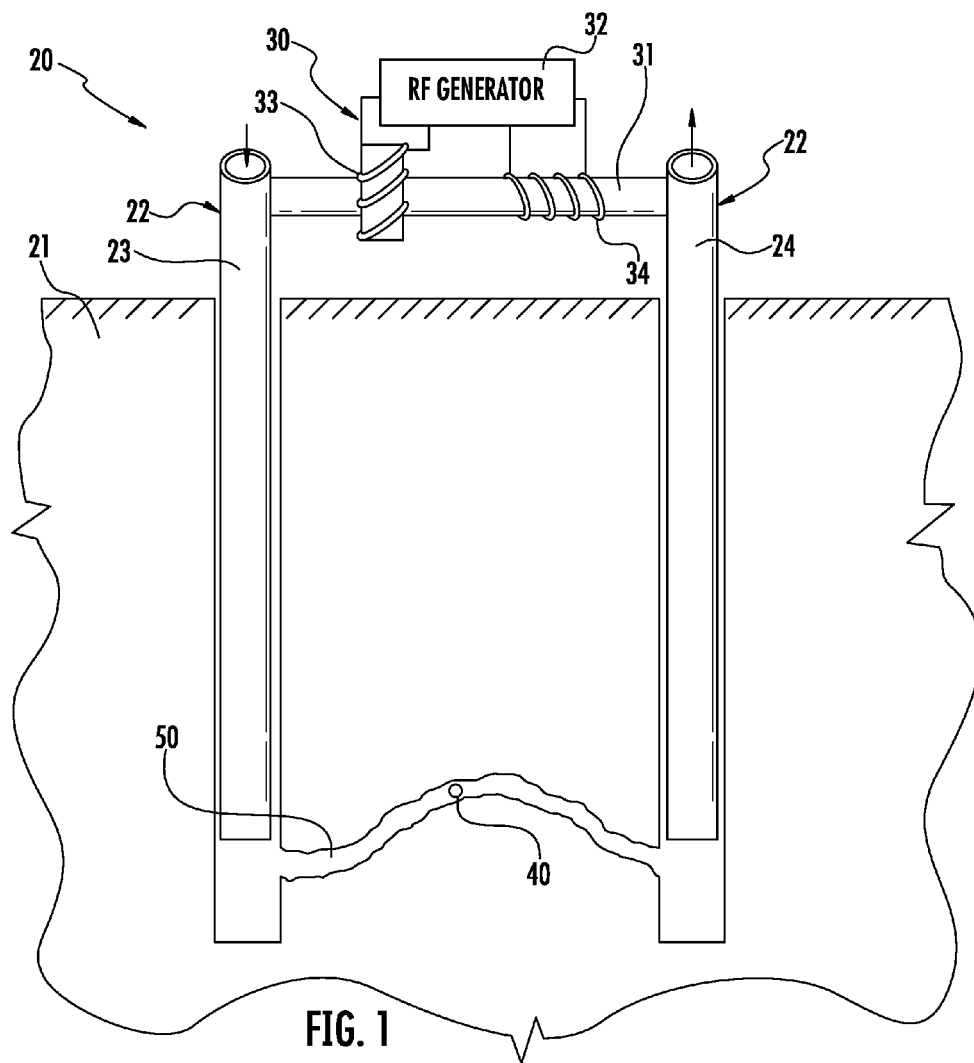
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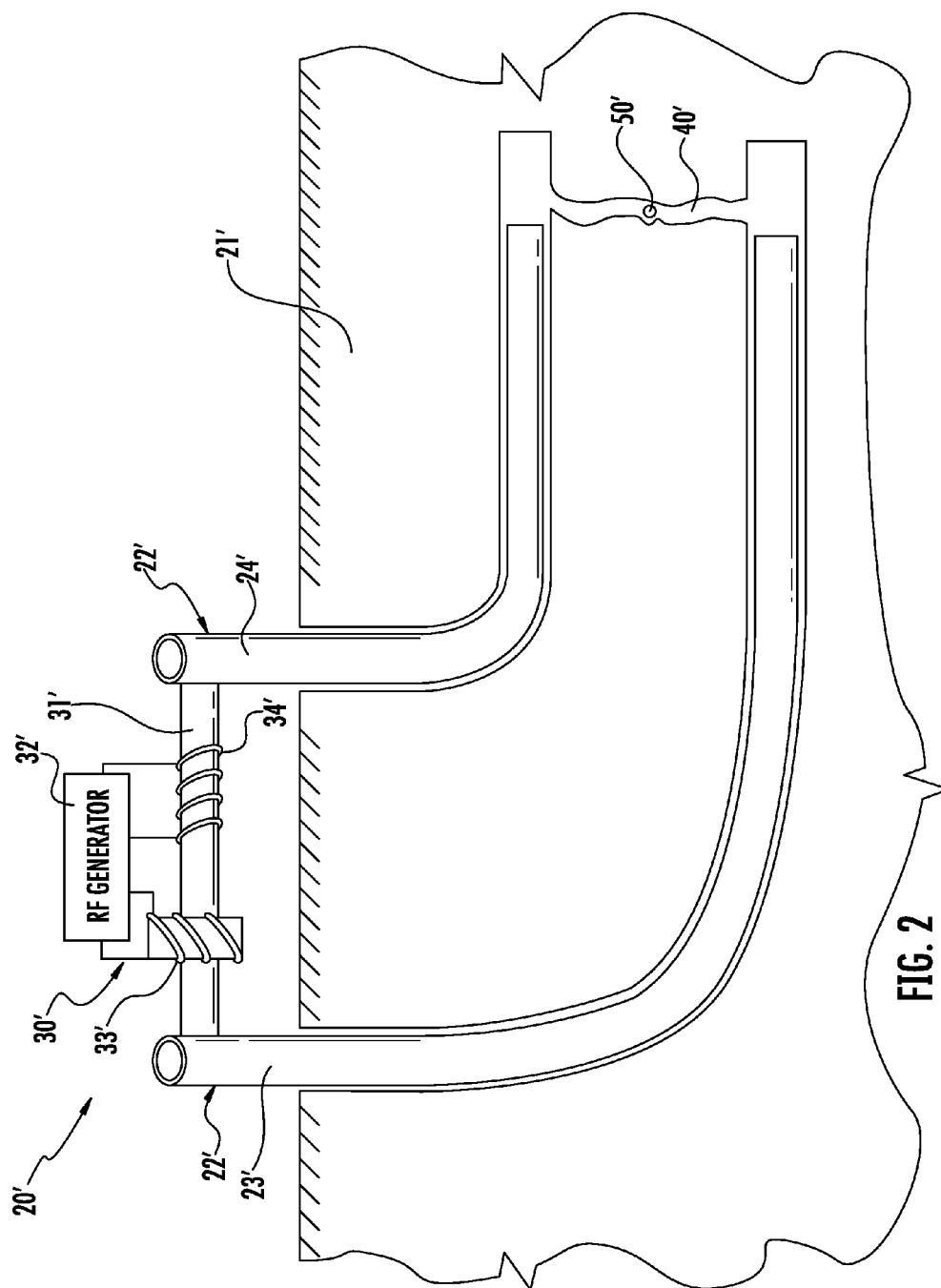
(57) **ABSTRACT**

A subterranean mapping system may include at least one electrically conductive element associated with a subterranean formation having a passageway therein. The subterranean mapping system may also include a radiofrequency (RF) source coupled to the at least one electrically conductive element to generate an electromagnetic (EM) field in the subterranean formation. The subterranean mapping system may also include a subterranean mapping device configured to be carried along a path of travel within the passageway and while sensing the EM field versus time.

**22 Claims, 9 Drawing Sheets**







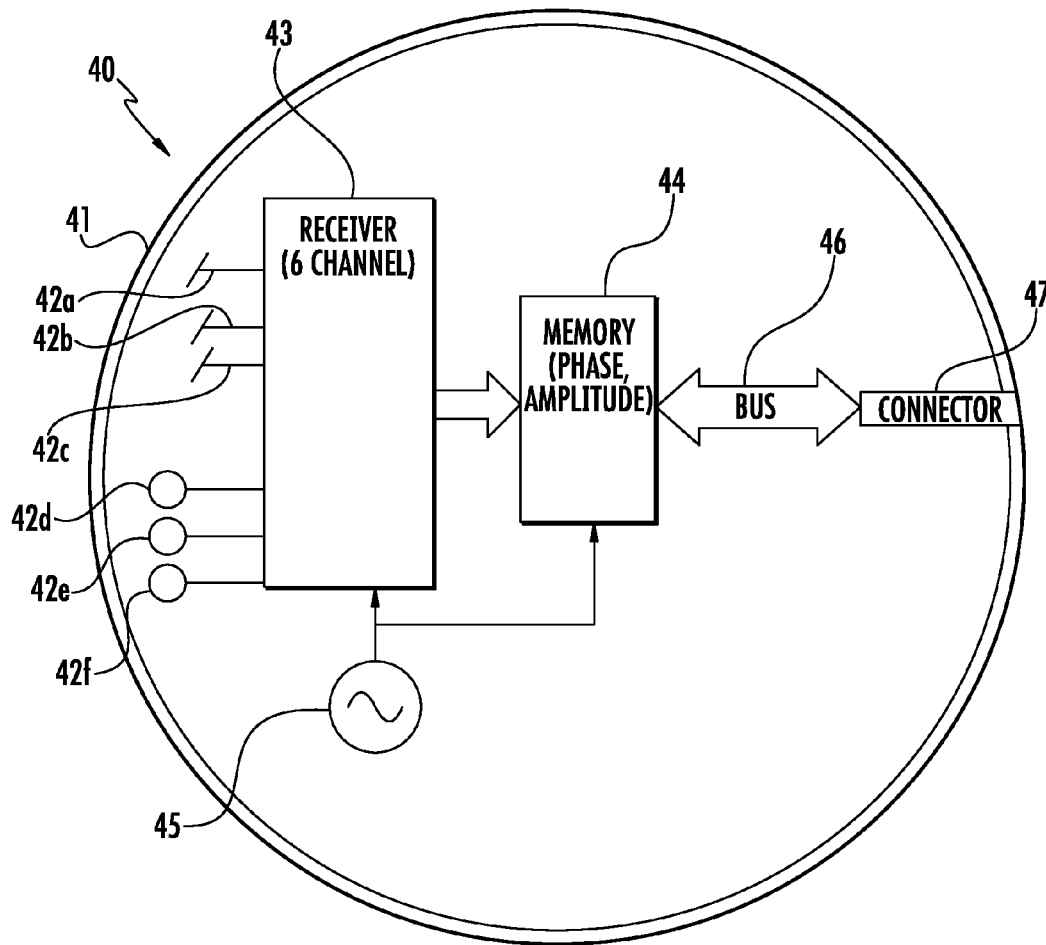


FIG. 3

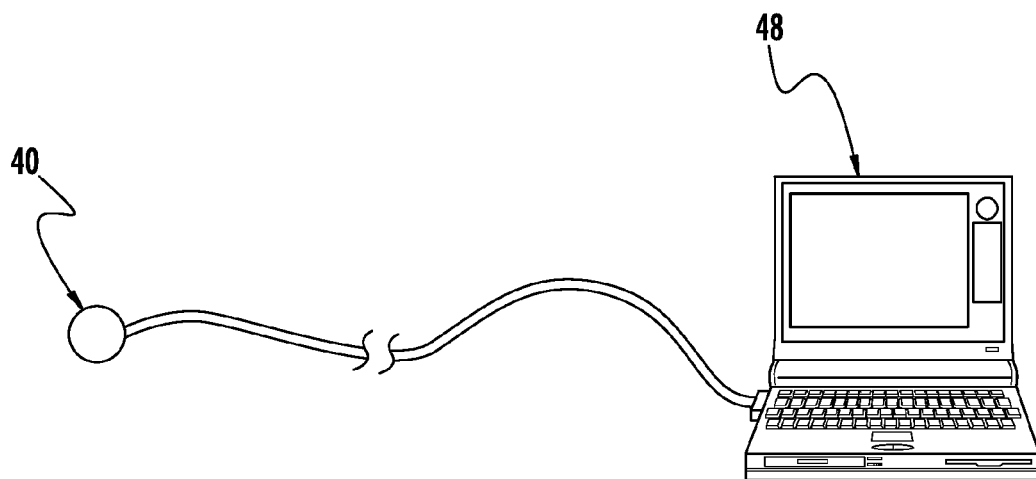


FIG. 4

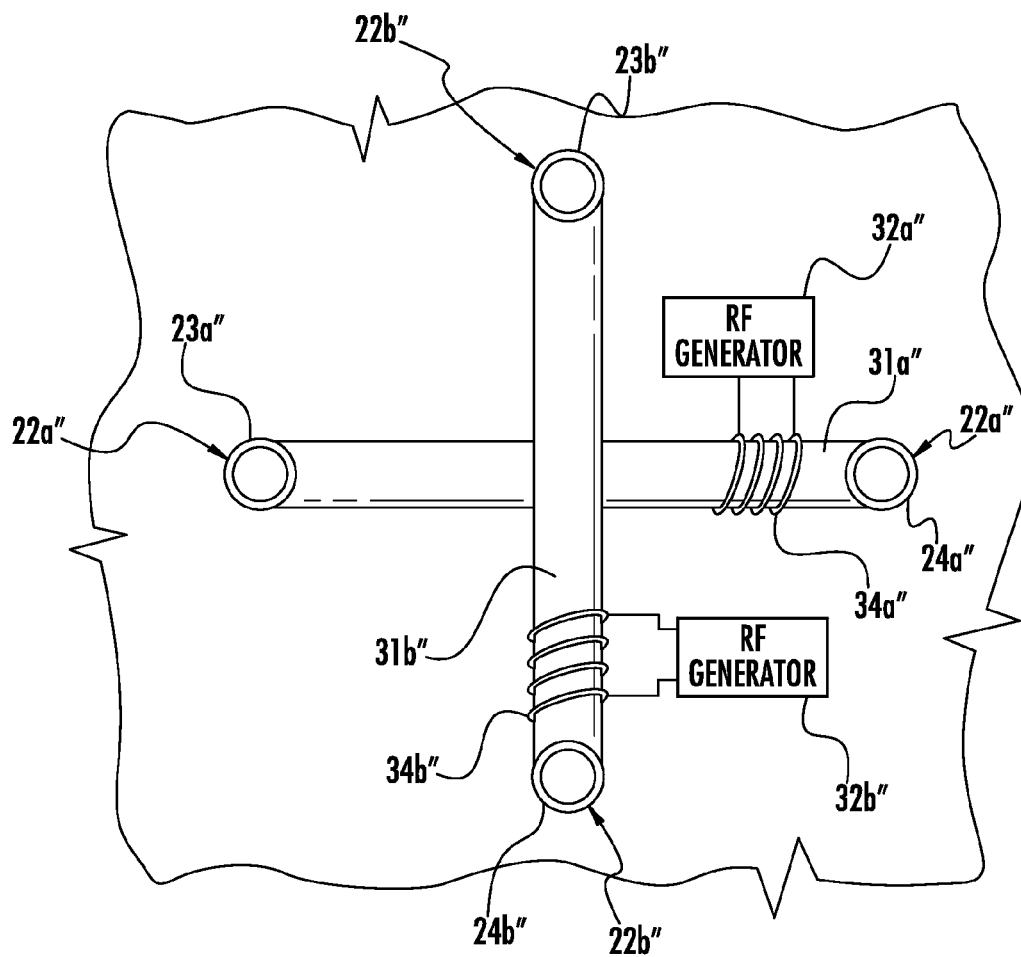


FIG. 5

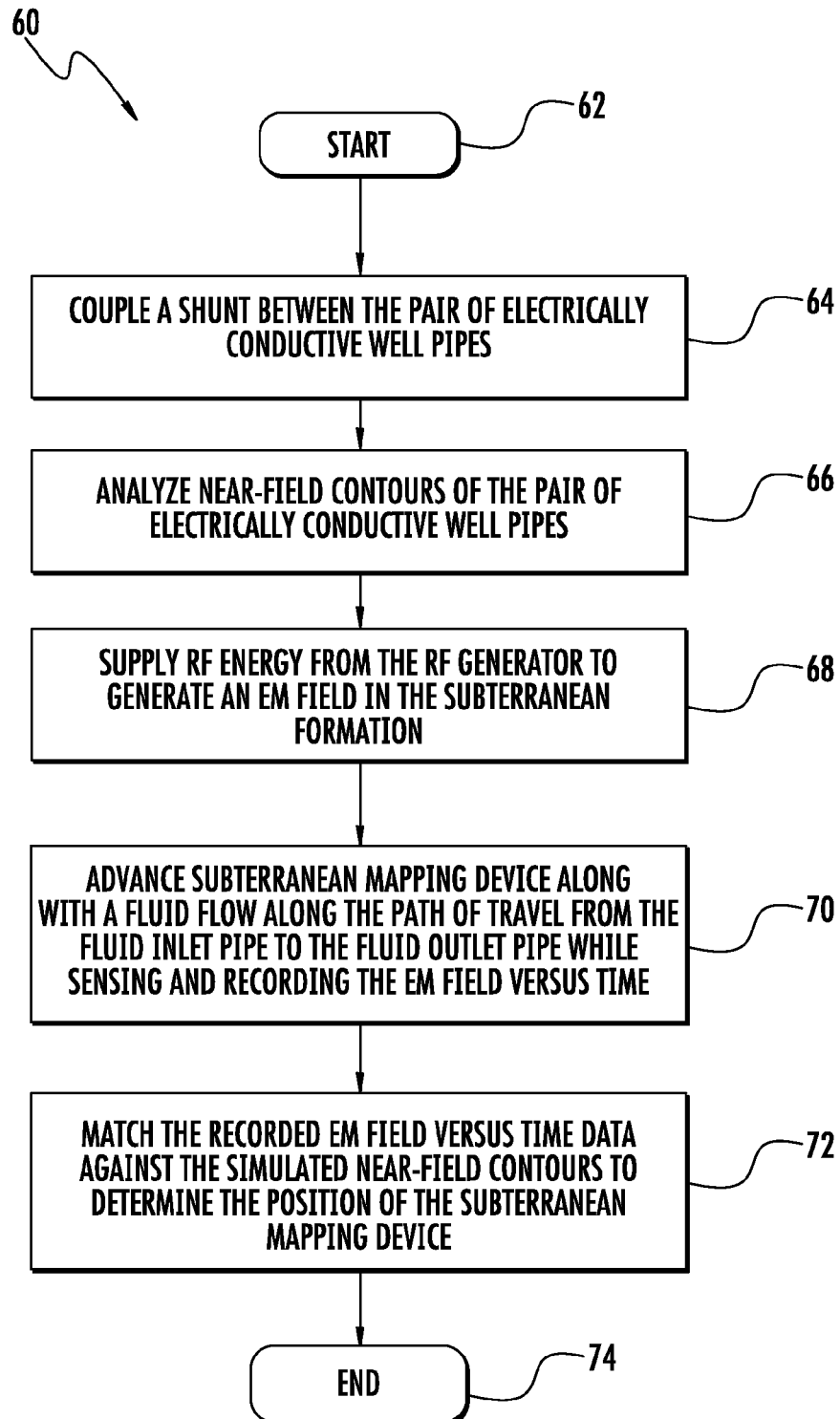
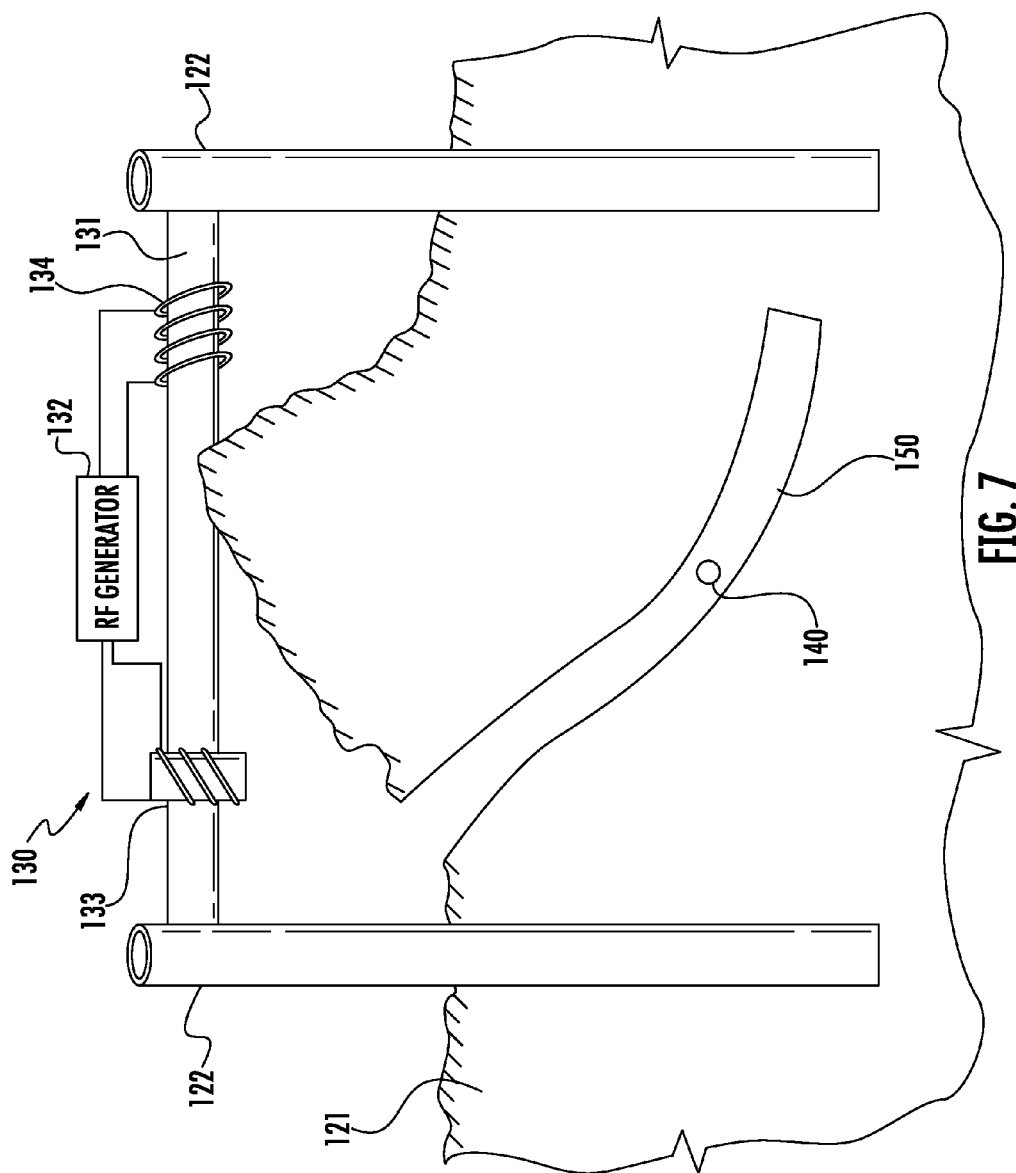


FIG. 6





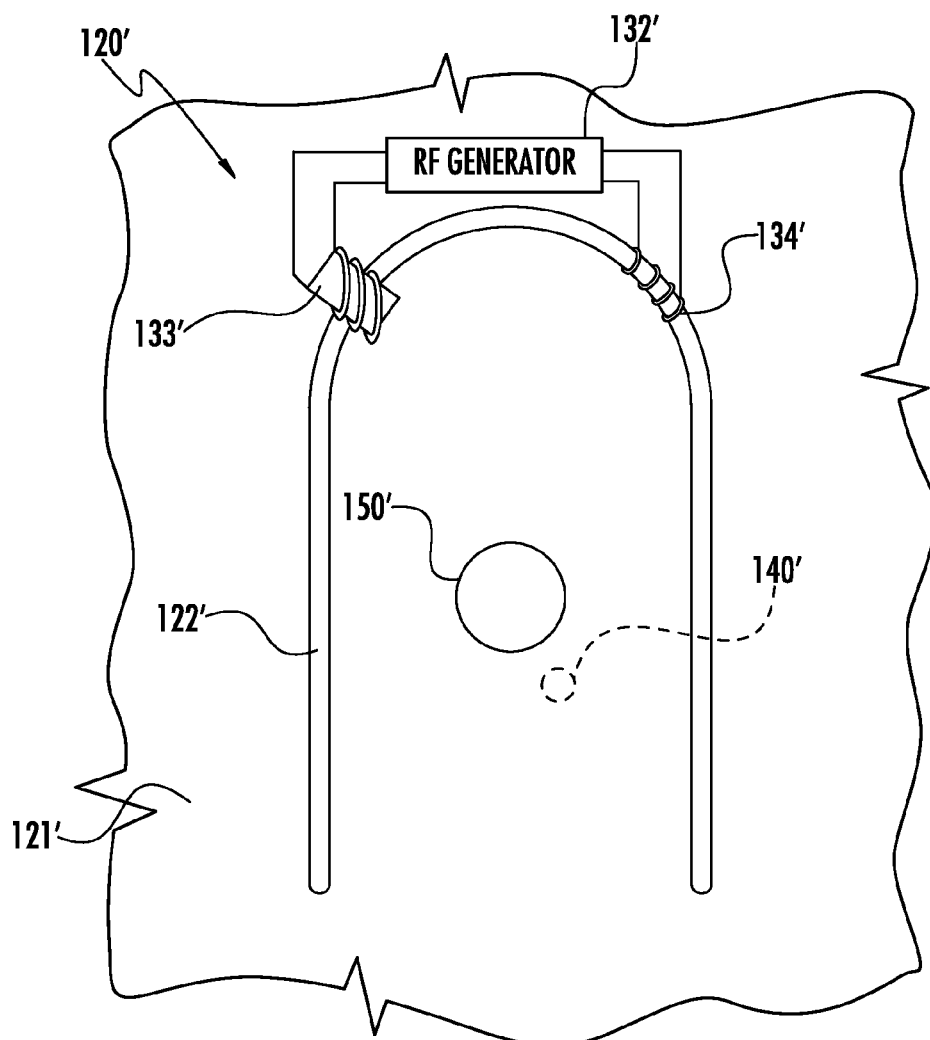


FIG. 8

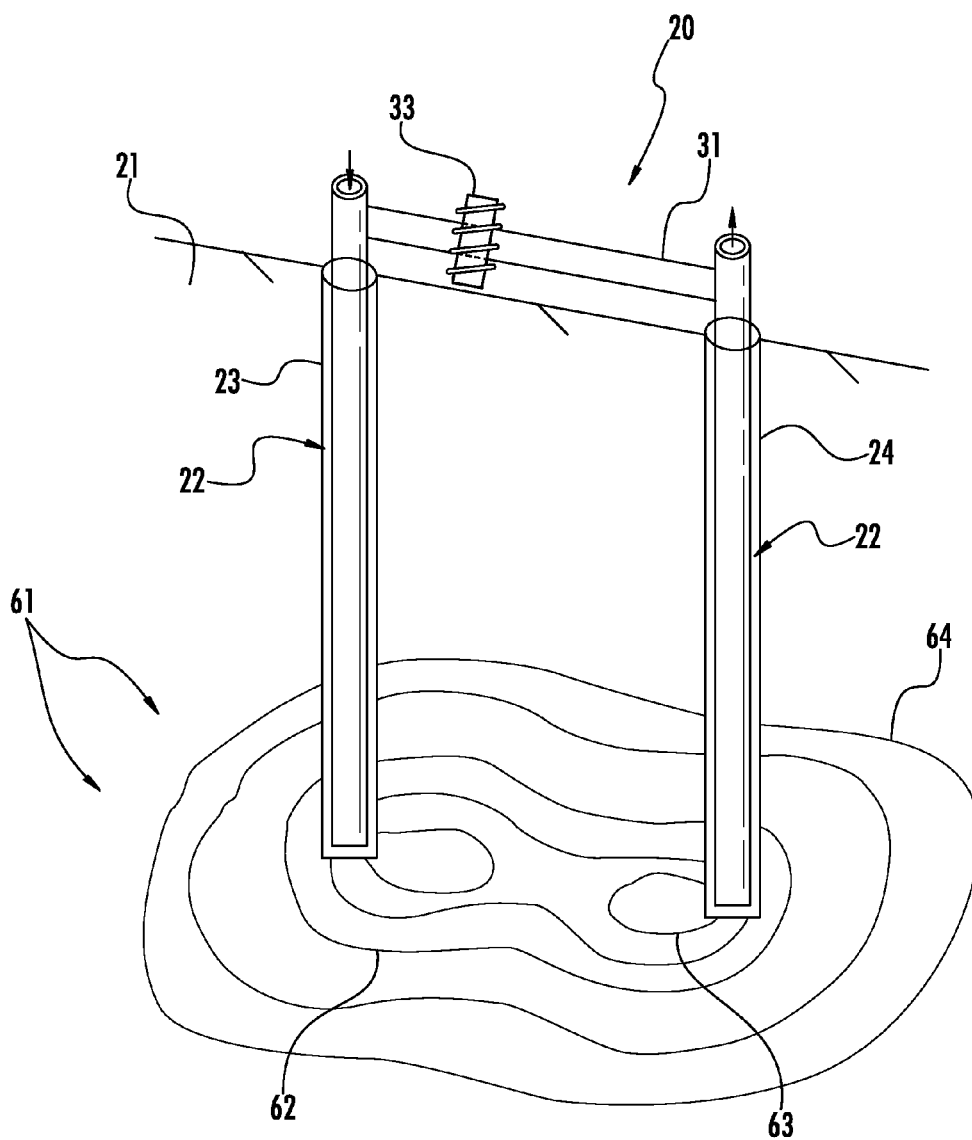


FIG. 9

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# **SUBTERRANEAN MAPPING SYSTEM INCLUDING ELECTRICALLY CONDUCTIVE ELEMENT AND RELATED METHODS**

## **FIELD OF THE INVENTION**

The present invention relates to the field of mapping, and, more particularly, to subterranean mapping.

## **BACKGROUND OF THE INVENTION**

Locating an object within a subterranean formation may be desirable. For example, it may be desirable to map a subterranean formation to locate buried pipes. Additionally, it may be desirable to locate other buried objects, for example, locating a human in a collapsed building or locating a human or object in a tunnel, cave, or other subterranean formation by mapping. Subterranean mapping techniques may include radio frequency (RF), ground penetrating radar (GPR), resistivity, micro-gravity, conductivity, electromagnetic, and magnetometry mapping techniques.

U.S. Pat. No. 6,097,189 to Arndt et al. discloses a system for locating an object disposed within a first medium having a conductivity and a permittivity may include one or more elements such as a transmitter for producing a transmit signal so that the transmit signal has at least one transmitter frequency. The transmitter may preferably be movable in a second medium adjacent to the first medium. A target antenna is provided for the object such that the target antenna produces a reradiated signal upon being radiated with the transmit signal. A first receiver is tuned to the reradiated signal frequency. A comparison unit may be used that has a memory element operative for storage of the indicia of conductivity. The comparison unit and the memory element have circuitry for comparing the transmit signal and the reradiated signal to determine a relative position between the transmitter and the target antenna using the indicia of conductivity.

Further improvements to mapping or tracking in a subterranean formation may be desirable. For example, it may be desirable to more quickly and easily map a subterranean object to more quickly repair a pipe, or locate a human, for example.

## **SUMMARY OF THE INVENTION**

In view of the foregoing background, it is therefore an object of the present invention to increase the efficiency of tracking a subterranean object.

This and other objects, features, and advantages in accordance with the present invention are provided by a subterranean mapping system that includes at least one electrically conductive element associated with a subterranean formation having a passageway therein. The subterranean mapping system also includes a radiofrequency (RF) source coupled to the at least one electrically conductive element to generate an electromagnetic (EM) field in the subterranean formation. The subterranean mapping system also includes a subterranean mapping device configured to be carried along a path of travel within the passageway and while sensing the EM field versus time. Accordingly, the subterranean mapping system may be particularly useful for mapping or tracking a subterranean object, for example, for locating a human.

The subterranean mapping system may further include a controller to be coupled to the subterranean mapping device and configured to map the path of travel based upon the sensed EM field, for example. The subterranean mapping device may include a portable housing, a plurality of antennas

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carried by the portable housing, and a receiver coupled to the plurality of antennas and configured to sense a plurality of phase and amplitude components of the EM field. The subterranean mapping device may also include a memory coupled to the receiver and configured to store the plurality of phase and amplitude components.

The at least one electrically conductive element may include a pair of spaced apart electrically conductive elements. The RF source may include a shunt coupled between the pair of electrically conductive elements, and an RF generator coupled to the shunt, for example.

The at least one electrically conductive element may include at least one electrically conductive and magnetic material. The RF source may include an RF generator, and a transformer coupled to the RF generator, for example.

The RF source may include an RF generator, and an electrically conductive winding coupled to the RF generator. The RF source may be above the subterranean formation, for example. The at least one electrically conductive element may be in the subterranean formation, for example.

A method aspect is directed to a method of mapping a path of travel of a subterranean mapping device in a subterranean formation having a passageway therethrough, and having at least one electrically conductive element associated therewith. The method includes supplying radiofrequency (RF) energy from an RF source coupled to the at least one electrically conductive element to generate an electromagnetic (EM) field in the subterranean formation. The method also includes advancing the subterranean mapping device along the path of travel within the passageway while sensing the EM field versus time.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic cross-sectional view of a subterranean formation including a subterranean mapping system in accordance with the present invention.

FIG. 2 is a schematic cross-sectional view of a subterranean formation including a subterranean mapping system in accordance with another embodiment of the present invention.

FIG. 3 is a schematic diagram of a subterranean mapping device of FIG. 1.

FIG. 4 is a schematic diagram of the subterranean mapping device coupled to a controller in accordance with the present invention.

FIG. 5 is a schematic top view of subterranean formation including a portion of a subterranean mapping system in accordance another embodiment of the present invention.

FIG. 6 is a flow chart of a method of mapping a path of travel in accordance with the present invention.

FIG. 7 is a schematic cross-sectional view of a subterranean formation including a subterranean mapping system in accordance another embodiment of the present invention.

FIG. 8 is a schematic top view of a subterranean formation including a subterranean mapping system in accordance another embodiment of the present invention.

FIG. 9 is a schematic diagram of a portion of the subterranean mapping device of FIG. 1 illustrating magnetic field strength contour.

## **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown.

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This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime and multiple prime notation is used to indicate similar elements in alternative embodiments.

Referring initially to FIG. 1, a subterranean mapping system **20** includes a pair of spaced apart electrically conductive well pipes **22** in a subterranean formation **21** containing a hydrocarbon resource. The pair of spaced apart electrically conductive well pipes **22** may be carbon steel, for example, or may other conductive materials. The spaced apart electrically conductive well pipes **22** may be well pipes in a SAGD well system, and may extend laterally.

The pair of electrically conductive well pipes **22** includes a fluid inlet pipe **23** and a fluid outlet pipe **24**. For example the fluid inlet pipe **23** may be an injector well, and the fluid outlet pipe **24** may be a producer well.

The subterranean mapping system **20** also includes a radiofrequency (RF) source **30** coupled to the pair of electrically conductive well pipes **22** to generate an electromagnetic (EM) field in the subterranean formation **21**. The RF source **30** is illustratively above the subterranean formation. In some embodiments, the RF source **30** may be within the subterranean formation.

The RF source **30** includes a shunt **31** coupled between the pair of electrically conductive well pipes **22**. The shunt **31** may be in the form of a steel pipe, for example, and is advantageously a temporary E and H field shunt. In other words, the shunt **31** is electrically conductive and magnetically permeable.

The RF source **30** also includes an RF generator **32** coupled to the shunt **31**. The RF generator **32** may be configured to generate RF energy at a frequency that may be at or below 1 MHz, and more particularly at or below 10 kHz, for example, or even relatively close to DC.

A transformer **33** is coupled between the RF generator **32** and the shunt **31**. The transformer **33** may be a toroidal transformer, for example, as described in application Ser. No. 12/839,927, assigned to the present assignee, and the entire contents of which are herein incorporated by reference. The transformer **33** excites electric currents on the shunt **31** and the pair of spaced apart electrically conductive well pipes **22**, and thus causes E-fields in the subterranean formation **21** (i.e., the electric field component of the EM field).

An electrically conductive winding **34** is coupled between the RF generator **32** and the shunt **31**. The electrically conductive winding **34** may be a helical, spirally wound electrically conductive winding, for example, and spirally wound around the shunt **31**. The electrically conductive winding **34** advantageously generates an H-field in the subterranean formation **21** (i.e. the magnetic field component of the EM field) by causing an H field in the shunt **31**. The combination of the electrically conductive well pipes **22**, the shunt **31**, and the electrically conductive winding **34**, forms, in a sense, a giant horseshoe electromagnet with the subterranean formation **21**. The above-noted combination conveys electric and magnetic near fields over a relatively large area in the subterranean formation **21**.

The transformer **33** and the electrically conductive winding **34** also are relatively uncoupled from one another, even though they are located on the same shunt **31**. This is advantageous as two separate radiolocation channels are available. The electrically conductive well pipes **22** may be considered, at times, a horseshoe magnet, and at other times an electrode

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pair, depending on whether a helical or toroidal winding is excited on the shunt **31**. The type of winding, helical or toroidal, determines whether electric currents or magnetic fields are applied to the electrically conductive well pipes **22**.

In operation, the pair of electrically conductive well pipes **22** are excited to carry electric currents and magnetic fields, which cause electric and magnetic near fields to surround the electrically conductive well pipes defining an antenna. As will be appreciated by those skilled in the art, the electrically conductive well pipes **22** convey magnetic fields across the underground gap between the ends thereof in the subterranean formation. At the underground gap, electric fields are created, and the magnetic near fields are time harmonic. Thus, a magnetic antenna is formed, and unlike conventional electric current antennas, each point in space has a unique combination of E-field amplitude, magnetic field amplitude H, and phase.

The subterranean mapping system **20** also includes a subterranean mapping device **40**. The subterranean mapping device **40** is configured to be carried along with a fluid flow along a path of travel from the fluid inlet pipe **23** to the fluid outlet pipe **24** and while sensing the EM field versus time.

Referring briefly to FIG. 2, in another embodiment, the pair of electrically conductive well pipes **22'** extends laterally within the subterranean formation **21'**. This configuration may be particularly advantageous for use with the steam assisted gravity drainage (SAGD) technique.

Referring now additionally to FIGS. 3 and 4, the subterranean mapping device **40** includes a portable housing **41**. The portable housing **41** may be spherically shaped, for example, to facilitate carrying by fluid flow. Antennas **42** are carried by the portable housing. The antennas **42** are phase centered and orthogonally mounted. Three antennas **42a**, **42b**, **42c**, are X, Y, and Z axis dipole antennas, respectively. Three other antennas **42d**, **42e**, **42f** are XY, YZ, and ZX plane loop antennas. In other words, the phase centered dipole and loop antennas resolve the E and H fields, respectively.

A receiver **43** is coupled to the plurality of antennas **42**. The receiver **43** is illustratively a 6-channel receiver and is configured to sense a plurality of phase and amplitude components of the electric and magnetic fields from each of the antennas **42**. Additional channels may be desired. A reference oscillator **45** is coupled to the receiver **43**. The reference oscillator **45** may be a quartz oscillator, for example. The receiver **43** may also include a gravimeter or inclinometer to sense receiver orientation.

A memory **44** is coupled to the receiver **43** and is configured to store the phase and amplitude components along with a time stamp. In other words, the electric and the magnetic filed amplitude and phase are recorded over time, so that underground electric and magnetic fields are mapped. In some embodiments, the electrically conductive winding **34** and the transformer **32** may be operated at different times or frequencies so two separate field sets are available for mapping and underground sensing. The memory **44** logs the absolute antenna phase relative to the reference oscillator **45**. More particularly, the memory **44** logs the E to H phase difference and absolute phase relative to time  $t=0$ . Advantageously, no bandwidth is being used, no pulses are generated, and no time of arrival techniques are used. The low frequencies for underground propagation generally preclude broad bandwidths for narrow pulses for time of arrival radiolocation.

The subterranean mapping device **40** also includes a digital data bus **46** connecting the memory **44** to an output connector **47**. The output connector **46** may couple to a coupling cable **49**, which in turn couples to the subterranean mapping device

40 to a controller 48, which may be in the form of a computer for extraction and processing of the recorded data, for example (FIG. 4). In some embodiments, the recorded data may be wirelessly transmitted to the computer 48.

The data extracted from or recorded in the memory 44 is compared to a simulated expected path of travel based upon a modelling of the pair of electrically conductive well pipes 22 and the shunt 31 (i.e. near field contours of the E and H fields). More particularly, expected E and H values corresponding to amplitude and phase are generated based upon the simulation. The actual recorded phase and amplitude components, i.e. the EM field, are compared by the controller 48 to the simulated amplitude and phase components to map or determine the path of travel.

This information may be particularly useful for determining a location of a wormhole 50 in the subterranean formation 21 (FIG. 1). As will be appreciated by those skilled in the art, a wormhole can reduce an amount of hydrocarbon resources collected, and decrease efficiency of the recovery. By determining the location of the wormhole 50, a repair may be performed more quickly and efficiently.

Applying magnetic field and electric currents to the pair of electrically conductive well pipes 22 produces, at each point in the subterranean formation 21, a unique set of the electric and magnetic near fields, the amplitudes and phases of which are used by the subterranean mapping device 40 to map its position. The bandwidth used is zero as pulse or time of arrival techniques are not needed, which may allow frequencies below 1 kilohertz to be utilized. At these frequencies, which constitute a low frequency window, electromagnetic energy may advantageously penetrate hundreds of meters or more into the subterranean formation 21.

Referring now to FIG. 5, in another embodiment, principles of the subterranean mapping system that apply to a pair of electrically conductive well pipes may similarly apply to two pairs of electrically conductive well pipes 22a", 22b". Each pair of electrically conductive well pipes 22a", 22b" includes respective RF source 30a", 30b" including a respective shunt 31a", 31b" and an RF generator 32a", 32b" coupled thereto, along with an electrically conductive winding 34a", 34b" as described in detail above. A respective transformer may also be coupled to each RF generator 32a", 32b". The two pairs of electrically conductive well pipes 22a", 22b" are positioned 90° out of phase from each other. This setup may advantageously result in increased accuracy mapping.

Referring now to the flowchart 60 in FIG. 6, a method aspect is directed to a method of a mapping a path of travel of a subterranean mapping device 20 in a subterranean formation 21 containing a hydrocarbon resource and having a pair of spaced electrically conductive well pipes 22 therein. The pair of electrically conductive well pipes 22 includes a fluid inlet pipe 23 and a fluid outlet pipe 24. Starting at Block 62, the method includes coupling a shunt 31 between the pair of electrically conductive well pipes 22 (Block 64). An RF generator 32 is also coupled to the shunt 31, and a transformer 33 is coupled to the between the RF generator and the shunt. An electrically conductive winding 34 is also coupled between the RF generator 32 and the shunt 31.

At Block 66, the near-field contours of the pair of electrically conductive well pipes 22 are analyzed via simulation. At Block 68, radiofrequency (RF) energy is supplied from the RF generator 32 to generate an electromagnetic (EM) field in the subterranean formation 21. A subterranean mapping device 50 is advanced, at Block 70, along with a fluid flow along the path of travel from the fluid inlet pipe 23 to the fluid outlet pipe 24 and while sensing the EM field versus time. More particularly, as noted above, the subterranean mapping device 50 records the parameters of time, E-field amplitude, H-field amplitude, E-to-H field difference, and absolute phase relative to time, t=0. At Block 72, the method includes

matching the recorded tag data or parameters against the simulated near-field contours of the pair of well pipes 22. A best match may be equivalent to the position of the subterranean mapping device 50 at the given time, t. The method ends at Block 74.

Referring now to FIG. 7, in another embodiment, the principles described above may be particularly advantageous for underground mapping operations, for example, for search and rescue. More particularly, the subterranean mapping system 120 may be particularly useful for mapping humans in a subterranean passageway. For example, the subterranean mapping system 120 may be used for tracking miners in a mine, for example, a coal mine or a cave.

The subterranean mapping system 120 includes a pair of electrically conductive elements 122 that are rigid and that may be driven, via drilling for example, into the subterranean formation 121 adjacent the subterranean passageway 150. The electrically conductive elements 122 may be electrically conductive pipes, for example, as described above with respect to FIGS. 1-5. In other embodiments, the electrically conductive elements 122 may be wires, for example, steel wire, and may be fed down respective holes in the subterranean formation 121, or even stretched horizontally on the surface. An RF source 130 is coupled to the electrically conductive elements 122 so the subterranean passageway 150 is between the electrically conductive elements. Similar to the embodiments described above, the RF source 130 includes a shunt 131, and an RF generator coupled to the shunt. The RF source 130 also includes a transformer coupled between the shunt 131 and the RF generator 132, and an electrically conductive winding also coupled between the shunt and the RF generator.

A human, for example, a mine worker, may carry a subterranean mapping device 140 along a path of travel within the subterranean passageway 150. The E and H fields are recorded by the subterranean mapping device 140, and may be recorded or wirelessly transmitted to a controller or computer above the subterranean formation 121 by, for example, a UHF radio repeater chain.

Similar to the embodiments described above with respect to FIGS. 1-5, the recorded data may be compared to simulated data to determine or map the path of travel. This may be particularly advantageous for more quickly locating a human in a search and rescue operation, for example. Of course, locating or mapping the path of travel of the human may be particularly advantageous for other applications, as will be appreciated by those skilled in the art. This technique may also be applied to other operations where mapping of a passageway in a subterranean formation may be desired.

Referring now to FIG. 8, in another embodiment, an electrically conductive element 122' is carried by the subterranean formation 121'. More particularly, the electrically conductive element 122' lies flat along the surface of the subterranean formation 121' or the ground in a U-shape or horseshoe shape. The electrically conductive element 122' may be wire, for example, copper wire. The length of the electrically conductive element 122' may be in a range of about 200-300 meters, for example. Of course, the length of the electrically conductive element 122' may be another length, for example, based upon the desired area of the subterranean formation 121' to be mapped. The electrically conductive element 122' is positioned so that a subterranean passageway 150' is within the arms of the U-shape. An RF source 130' is coupled to the electrically conductive element 122' so that an EM field is generated in the subterranean formation 121'. More particularly, an RF generator 131' is coupled to the electrically conductive element 122'. A transformer 133' is coupled between the RF generator 131' and the electrically conductive element 122', and an electrically conductive winding 134' is coupled between the RF generator and the electrically conductive

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element. The subterranean mapping device **140'** is similar to that described above, and the principles of operation also described above, are similarly applicable to this embodiment.

A related method is directed to a method of a mapping a path of travel of a subterranean mapping device **140** in a subterranean formation **121** having a passageway **150** there-through, and having at least one electrically conductive element **122** associated therewith. The method includes supplying RF energy from an RF source **130** coupled to the at least one electrically conductive element **122** to generate an electromagnetic (EM) field in the subterranean formation **121**. The method also includes advancing the subterranean mapping device **140** along the path of travel within the passageway **150** while sensing the EM field versus time.

The penetration of electromagnetic fields in a subterranean formation **121** is related to the radio frequency skin depth in the subterranean formation. Athabasca oil sand formation overburden may have a varying electrical conductivity between about 0.1 and 0.5 mhos per meter, and for 0.2 meters electrical conductivity the radio frequency skin depth can be calculated to be 356 meters at 10 hertz. Rich Athabasca oil sand proper may have an electrical conductivity of 0.005 mhos/meter, which may correspond to a radio frequency skin depth of about 356 meters at 1000 Hertz. So, overburden rather than payzone conductivity may primarily determine the operating frequency. As many such deposits are within 500 meters of the surface, operating frequencies for the present embodiments may be between about 0.5 and 500 hertz, for example, for this resource.

Referring now additionally to FIG. 9, an isometric view of a portion of the subterranean mapping system **20** showing contour plots **61** of simulated realized magnetic field strength, in a plane between the ends of spaced apart electrically conductive well pipes **22** is illustrated. One watt was applied to the transformer **33** at a radio frequency of 100 hertz. The well pipes **22** were simulated to be 100 meters long. The subterranean formation **21** was typical of a shallow hydrocarbon formation in the Athabasca region of Canada. A first contour line **62** is  $1.2 \times 10^{-10}$  amperes/meter, a second contour line **63** is  $1.5 \times 10^{-10}$  amperes/meter, and a third contour line **64** is  $6.0 \times 10^{-11}$  amperes/meter. Of course, contours also exist for the electric fields, but are not shown, and yet another set of electric and magnetic field contours exist for excitation using an electrically conductive winding (also not shown). As can be appreciated by those skilled in the art, the well pipes **22** provide in-situ antennas to create electric and magnetic fields relatively deep underground. A unique electromagnetic solution set exists for each point in space in the subterranean formation **21**.

Many modifications and other embodiments of the invention will also come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.

That which is claimed is:

1. A subterranean mapping system comprising:

at least one electrically conductive element associated with a subterranean formation having a passageway there-through;

a radiofrequency (RF) source coupled to said at least one electrically conductive element to generate an electromagnetic (EM) field in the subterranean formation; and

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a subterranean mapping device configured to be carried along a path of travel within the passageway and while sensing the EM field versus time.

2. The subterranean mapping system of claim 1, further comprising a controller to be coupled to said subterranean mapping device and configured to map the path of travel based upon the sensed EM field.

3. The subterranean mapping system of claim 1, wherein said subterranean mapping device comprises:

a portable housing;

a plurality of antennas carried by said portable housing;

a receiver coupled to said plurality of antennas and configured to sense a plurality of phase and amplitude components of the EM field; and

a memory coupled to said receiver and configured to store the plurality of phase and amplitude components.

4. The subterranean mapping system of claim 1, wherein said at least one electrically conductive element comprises a pair of spaced apart electrically conductive elements.

5. The subterranean mapping system of claim 4, wherein said RF source comprises:

a shunt coupled between said pair of electrically conductive elements; and

an RF generator coupled to said shunt.

6. The subterranean mapping system of claim 1, wherein said at least one electrically conductive element comprises at least one electrically conductive and magnetic material.

7. The subterranean mapping system of claim 1, wherein said RF source comprises:

an RF generator; and

a transformer coupled to said RF generator.

8. The subterranean mapping system of claim 1, wherein said RF source comprises:

an RF generator; and

an electrically conductive winding coupled to said RF generator.

9. The subterranean mapping system of claim 1, wherein said RF source is above the subterranean formation.

10. The subterranean mapping system of claim 1, wherein said at least one electrically conductive element is in the subterranean formation.

11. The subterranean mapping system of claim 1, wherein said at least one electrically conductive element is carried by the subterranean formation.

12. A subterranean mapping system comprising:

a pair of electrically conductive elements associated with a subterranean formation having a passageway there-through;

a radiofrequency (RF) source coupled to said pair of electrically conductive elements to generate an electromagnetic (EM) field in the subterranean formation, and comprising

a shunt coupled between said pair of electrically conductive elements, and

an RF generator coupled to said shunt;

a subterranean mapping device configured to be carried along a path of travel within the passageway and while sensing the EM field versus time; and

a controller to be coupled to said subterranean mapping device and configured to map the path of travel based upon the sensed EM field.

13. The subterranean mapping system of claim 12, wherein said subterranean mapping device comprises:

a portable housing;

a plurality of antennas carried by said portable housing;

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a receiver coupled to said plurality of antennas and configured to sense a plurality of phase and amplitude components of the EM field; and  
 a memory coupled to said receiver and configured to store the plurality of phase and amplitude components.

**14.** The subterranean mapping system of claim **12**, wherein said shunt comprises an electrically conductive and magnetic material.

**15.** The subterranean mapping system of claim **12**, further comprising a transformer coupled between said RF generator and said shunt.

**16.** The subterranean mapping system of claim **12**, further comprising an electrically conductive winding coupled between said RF generator and said shunt.

**17.** The subterranean mapping system of claim **12**, wherein said RF source is above the subterranean formation.

**18.** A method of a mapping a path of travel of a subterranean mapping device in a subterranean formation having a passageway therethrough and having at least one electrically conductive element associated therewith, the method comprising:

supplying radiofrequency (RF) energy from an RF source coupled to the at least one electrically conductive ele-

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ment to generate an electromagnetic (EM) field in the subterranean formation; and  
 advancing the subterranean mapping device along the path of travel within the passageway while sensing the EM field versus time.

**19.** The method of claim **18**, further comprising coupling a controller to the subterranean mapping device to map the path of travel based upon the sensed EM field.

**20.** The method of claim **18**, wherein advancing a subterranean mapping device comprises advancing a subterranean mapping device comprising a portable housing, a plurality of antennas carried by the portable housing, a receiver coupled to the plurality of antennas and configured to sense a plurality of phase and amplitude components of the EM field, and a memory coupled to the receiver and configured to store the plurality of phase and amplitude components.

**21.** The method of claim **18**, wherein supplying RF energy from the RF source comprises supplying RF energy from an RF source above the subterranean formation.

**22.** The method of claim **18**, wherein supplying RF energy from the RF source comprises supplying RF energy from the RF source coupled to the at least one electrically conductive element in the subterranean formation.

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